Precise Time and Time Interval, Astrometry and Astrophysics

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LONG-TERM GOAL

This program develops, implements, and tests, on telescopes and precise time systems, technologies for the determination of the positions and motions of celestial bodies, the motions of the Earth, and precise time in order to provide the astronomical and timing data required by the Navy and other components of the Department of Defense (DoD) for navigation, precise positioning, command, control, and communications, as well as developing sensor systems for surveillance. The primary goal is to improve the accuracy, quantity, timeliness, and reliability of the operational support provided by the U.S. Naval Observatory (USNO) to DoD in the areas of precise time and time interval, Earth rotation and orientation, and inertial reference frames based on star, planet, and extragalactic source positions. Further technologies will be developed to improve sensor technologies for surveillance, targeting, and navigation.

OBJECTIVES

The USNO Mission, as the only U.S. institution engaged in the practical application of astrometry and timekeeping, is to provide DoD with precise time and celestial position data and also to promulgate such data as directed by public law through the publication of the astronomical ephemeris. The R&D supported by this area allows the USNO to fulfill its operational mission responsibilities in a field which has an ever evolving technology in sensors, communications, systems control, and analysis. Specific objectives of this program include:

- Improvement of the U.S. Master Clock systems both in Washington and at Schriever AFB, the master control station for GPS, by evaluating and incorporating new types of clocks, real-time clock monitoring systems, and time scale algorithms for clock ensembles.

- Evaluation and refinement of various time transfer (clock synchronization) techniques especially using GPS in order to provide and sustain a tightly coupled worldwide DoD time system.

- Improvements to the fundamental ephemerides, which are the bases for positions of solar system bodies and the fundamental stellar reference system.

- Improvements to the algorithms for artificial satellite motions and their orbits especially in the area of GPS orbits in order to improve the accuracy of UT1 and polar motion.

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14. ABSTRACT

This program develops, implements, and tests, on telescopes and precise time systems, technologies for the determination of the positions and motions of celestial bodies, the motions of the Earth, and precise time in order to provide the astronomical and timing data required by the Navy and other components of the Department of Defense (DoD) for navigation, precise positioning, command, control, and communications, as well as developing sensor systems for surveillance. The primary goal is to improve the accuracy, quantity, timeliness, and reliability of the operational support provided by the U.S. Naval Observatory (USNO) to DoD in the areas of precise time and time interval, Earth rotation and orientation, and inertial reference frames based on star, planet, and extragalactic source positions. Further technologies will be developed to improve sensor technologies for surveillance, targeting, and navigation.

15. SUBJECT TERMS

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- Improvement in the models and algorithms used for Earth rotation and orientation predictions to fulfill DoD systems autonomy requirements.

- Improvements to astronomical reference frames based on star, planet, and quasar positions, including increases in precision, benchmark density, and inertial stability.

- Development of radio/IR/optical interferometry and charge coupled device (CCD) technology for precision astronomical measurements, including satellite tracking applications, and expansion of precision star catalogs to the infrared wavelengths by exploiting IR technology.

APPROACH

Improvements to the precision of the Master Clock are being developed to meet future needs in precise positioning for targeting. The development of atomic fountain technology is underway to improve the precision of the Master Clock. The cesium fountain has met its short-term performance goals, and we have analyzed the medium- to long-term performance up to several days and have designed a large portion of the first rubidium fountain. The existing R&D device has been completed and is performing long term evaluations that are referenced to the USNO Master Clock. Work has progressed on a second, more heavily engineered R&D fountain. This device will be built with rubidium atoms (to lower collisional frequency shifts). We are investigating alternate laser synthesis methods for trapping and cooling the atom, and are building the vacuum chamber and microwave interrogation regions.

Various methods of time transfer – worldwide clock synchronization to UTC (USNO) – must be evaluated. DoD users operationally get their time directly from GPS (UTC (USNO)) at the 30 - 1000 nanosecond level. However other techniques can yield substantial improvement. GPS common view provides absolute synchronization at the 10 nanosecond level, but other methods, including carrier phase GPS tracking, laser reflection, fiber transmission, global broadcasting, the WAAS, and two-way radio transmissions, in some cases have demonstrated the ability to provide synchronization at the nanosecond, or better, level. All of these techniques need further refinement for use in operational systems.

At optical wavelengths, CCD device applications to astrometry are underway. These devices, of high quantum efficiency, dynamic range, and linear response, promise to revolutionize many types of astronomical observations. Development of hardware and software for CCD detection systems suitable for high precision star positions is a major focus of work at USNO’s Flagstaff station.

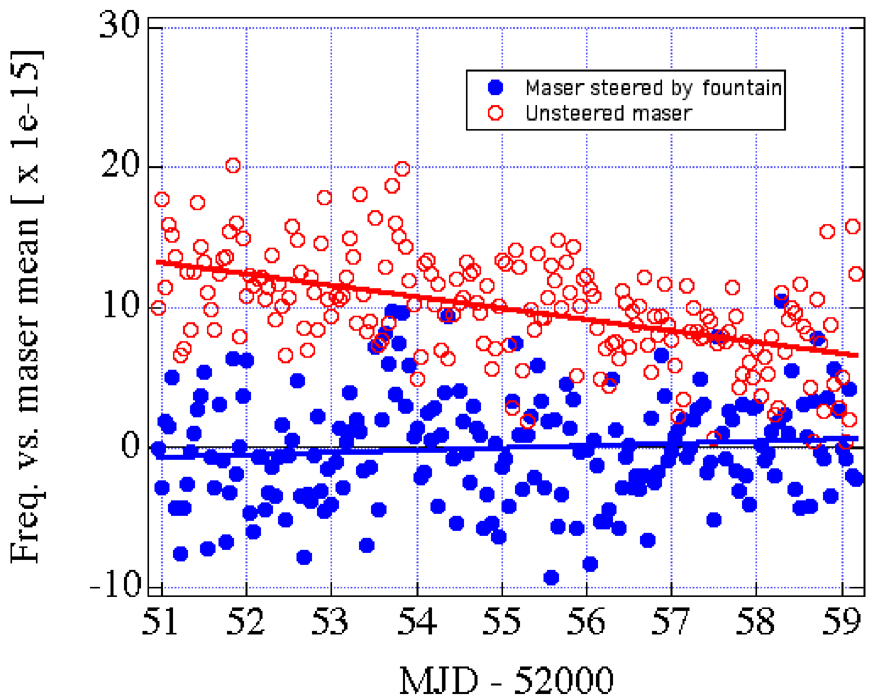
A new approach to determine very accurate star positions with such detectors on a stationary telescope, the Sloan Digital Sky Survey (SDSS), covering one quarter of the entire sky, is being investigated. The SDSS is scheduled to begin routine survey operations this FY. Once underway, this survey will begin to generate accurate astrometric positions for stars from magnitude 13 to nearly magnitude 23 over a significant fraction of the sky. A 1.3 m wide field telescope is being developed for Flagstaff.

Research on the capability of a CCD focal plane to make precise measurements under space conditions has been and continues to be supported under 6.2 funding.

WORK COMPLETED

The short term performance of the cesium fountain has been improved to levels as good as 1.5×10^{-13}/sqrt(tau). Work on many aspects of the device has resulted in continuous operation for up to 10 days. In addition, operation has been demonstrated with a steered hydrogen maser as the output of the fountain. When operating with a steered output, the fountain detected and removed the drift of the maser at the level of better than 2×10^{-16}/day.

Several design studies for the construction of the rubidium fountain have been completed. All but two major technological approaches have been frozen in the design, those being an in-vacuum atom shutter and details of the laser synthesis. We have an acceptable laser synthesis system based on diode pumped solid state lasers, but continue to research a telecom laser system.



Demonstration of the Cs fountain steering out the drift of a hydrogen maser. When operating with the steered output, the fountain detected and removed the drift of the maser at the level of better than $2x10^{-16}$/day. The two data sets are offset vertically for clarity.

The program in GPS carrier phase time transfer has produced an improved IGS (International GPS Service) timescale product that has been released to the IGS community. This scale routinely produces a globally distributed time scale with a frequency stability of 2×10^{-15} at one day.

USNO is working with NAVSYS to develop a 16 element phased array antenna working with a dual frequency 12 channel GPS P/Y code time monitor station receiver. The addition of the phased array antenna will allow for much improved receiver measurement noise because of an almost 12 dB increase in S/N and much reduced multi-path due to the directional nature of the antenna. This system should also allow for real time GPS carrier phase ambiguity resolution that should lead to picosecond

level time transfer. The antenna and receiver were delivered to USNO in Sept 02. In FY03, tests will be underway to evaluate its performance.

Imaging and spectroscopic observations continued smoothly during FY02, though progress has suffered somewhat because the observing conditions (weather) have been worse this year than normal. The two-year mark (of the five-year survey) is now passed. Just over 4,000 square degrees of the survey area have now been scanned, and spectra have been obtained for over 350,000 objects. A major public data release, consisting of over 2,800 square degrees of imaging data and 200,000 spectra, is scheduled for January, 2003.

Significant USNO/astrometry highlights this year:

- The astrometric performance continues to easily meet the Survey scientific requirements and has improved over the past year, primarily due to the increased availability of the USNO CCD Astrographic Catalog (UCAC) as well as improvements in the software which detects and measures the positional centers of objects outside of the astrometric pipeline.

- For those areas of the sky where UCAC coverage is available, the astrometric internal errors are typically better than 50 milliarcseconds per coordinates (rms) and better then 90 milliarcseconds per coordinate when UCAC coverage is not available and the sparser Tycho2 catalog is used.

- The astrometric software pipeline, developed and maintained by USNO astronomers, is reliable and robust and has been operating routinely. No major changes to the pipeline were needed this year.

- USNO astronomers continue to support the observation aspect by ensuring that astrometric tools are available at the telescope to assist observers to point the telescope correctly, and to monitor the telescope tracking during scanning.

SDSS should continue to operate routinely for the next 2-1/2 years. Operations are quite stable.

RESULTS

The cesium fountain has demonstrated continuous operation with a steered output for up to 10 days with a short-term stability of 1.5×10^{-13} at one second. Major portions of the rubidium fountain design are done, and several subsystems have been built. The GPS carrier phase project has produced a globally distributed time scale with a stability of 2×10^{-15} at one day.

One of the main goals of the SDSS is to discover and spectroscopically classify and confirm a large number of Quasi-Stellar Objects (QSOs, or Quasars). These objects are extremely distant and exhibit no detectable motion across the sky (proper motion). Current astrometric catalogs use stars within our own Milky Way Galaxy to provide positional references, but these stars are relatively near-by, and their proper motions introduce errors into the catalogs over time. An astrometric catalog of QSOs, on the other hand, will not suffer from this problem and will provide essentially an “inertial reference frame” free from these effects.

While the SDSS sky coverage continues to grow, so will the coverage of USNO’s UCAC catalog. This will enable the astrometric pipeline to reduce more and more SDSS data using this new catalog. Since

UCAC reaches several magnitudes fainter than existing astrometric catalogs, SDSS will be able to reduced faint stars directly against the catalog. This procedure will significantly improved the SDSS astrometry. When the UCAC sky coverage is complete (expected in 2003), all SDSS observations will be reduced using UCAC.

The large SDSS database of stellar positions, magnitudes and colors will be compared with the forthcoming USNO-B catalog to refine the proper motions measures of tens of millions of stars. Such studies will teach us much about the motions of stars in our part of our Milky Way Galaxy and will lead to further improvements in astrometry in general.

The SDSS should complete observations in CY 2005 at which time the telescope and instrumentation will almost certainly be used for further survey work. Several possibilities have been mentioned, including the continuation of the Survey to lower Galactic latitudes, covering all of the northern sky; moving the telescope to the southern hemisphere to continue the survey into the southern sky; doing “rapid” surveys for brighter objects only; using the spectrographic capabilities to obtain spectra of hundreds of thousands, and even millions, of stars for accurate spectral classification (including spectroscopic parallaxes) and radial velocities. All of these possibilities could lead to significant improvements in the astrometry of faint stars.

IMPACT/APPLICATION

In the area of precise time and time interval the stability of the Master Clock is now about 1 ns rms/day. This stability will be improved by two orders of magnitude through the use of a Rubidium Fountain. This development will lead to time performance at the 100 picosecond level. Improvements in time transfer at this level are also being developed via GPS carrier phase time transfer, GPS receiver and antenna technology, and the WAAS. With this long-term stability and accuracy in time it appears promising to achieve worldwide time stability on the nanosecond level and the resulting accuracy in navigation and targeting of precise munitions should approach the one-meter level. In the area of astrometry, the development of large format CCD focal plane arrays will bring forward the determination of precise positions of a large number of stars. Space astrometry will yield the precise positions of stars at the submicroarcsecond. These star positions are needed for present and future DoD space operations. This will allow these objects to be employed for the precise determination of satellite positions, improved geolocation, and space navigation.

TRANSITIONS

Due to the unique role of the USNO as the standard for Navy and DoD PTTI operations, every successful exploratory development study leads immediately to an improved operational capability. As was stated last year, the 6.2 technology development emphasis is shifting to developing improved time standards and time transfer. The successful development of TTR12 receiver will improve GPS time. In the area of earth orientation parameters, the determination of UT1 and polar motion has transitioned from 6.2, via 6.4 into operations.

RELATED PROJECTS

This research is highly coordinated with work performed nationally and internationally. The clock work is coordinated with programs at NIST in the US, BIPM, LPTF and Ecole Normal Superior in

France and the PTB in Germany. The astrometry work is coordinated with research at universities and national facilities such as the National Radio Astronomy Observatory (NRAO) and the National Optical Astronomy Observatory (NOAO). For example the program to develop the InSb detector array is a joint effort with NOAO. The development of large focal plane arrays for astrometry at optical wavelengths is being pursued in a joint program, the Sloan Digital Sky Survey (SDSS) with the Astrophysical Research Consortium (members Princeton, Universities of Chicago, Washington, Fermilab).

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